Environ Earth Sci
DOI 10.1007/s12665-010-0832-8

ORIGINAL ARTICLE

The dispersion of fibrous amphiboles by glacial processes in the area surrounding Libby, Montana, USA

William H. Langer · Bradley S. Van Gosen · Gregory P. Meeker · David T. Adams · Todd M. Hoefen

Received: 23 July 2010 / Accepted: 30 October 2010

Abstract Mining operations began at a world-class vermiculite deposit at Vermiculite Mountain near Libby, Montana, circa 1920 and ended in 1990. Fibrous and asbestiform amphiboles intergrown with vermiculite ore are suspected to be a causative factor in an abnormally high number of cases of respiratory diseases in former mine and mill workers, and in residents of Libby. The question addressed in this report is whether some of the amphibole from Vermiculite Mountain could have been dispersed by Pleistocene glacial processes rather than by human activity after vermiculite mining began. The history of Pinedale glaciation in the Libby area provides a framework for estimating the presence and distribution of asbestiform amphiboles derived from Vermiculite Mountain and found in naturally occurring sediments of Glacial Lake Kootenai that underlie the Libby Valley area. There were two situations where sediments derived from Vermiculite Mountain were deposited into Glacial Lake Kootenai: (1) as lake-bottom sediments derived from meltwater flowing down Rainy Creek when the valley south of Vermiculite Mountain was free of ice but active ice still covered Vermiculite Mountain; and (2) as lake-bottom sediments eroded from the Rainy Creek outwash and re-deposited during a re-advance of the Purcell Trench Glacier lobe near Moyie Springs, Idaho.

Keywords Libby · Montana · Amphibole asbestos · Glacial geology · Glacial Lake Kootenai

W. H. Langer (✉) · B. S. Van Gosen · G. P. Meeker · D. T. Adams · T. M. Hoefen
U.S. Geological Survey, Denver, CO, USA
e-mail: blanger@usgs.gov

Introduction

The town of Libby is located in northwestern Montana (Fig. 1). A world-class vermiculite deposit occurs at Vermiculite Mountain in the igneous Rainy Creek Complex approximately 10 km northeast of Libby (Boettcher 1967). Mining operations began at the deposit circa 1920 and ended in 1990. Fibrous and asbestiform amphiboles intergrown with vermiculite ore produced at Vermiculite Mountain are suspected to be a causative factor in an abnormally high number of cases of respiratory diseases in former mine and mill workers, in some of the residents of Libby, and others exposed to the Libby vermiculite ore shipped to other parts of the country (Horton et al. 2008; Sullivan 2007; Peipins et al. 2003).

The amphiboles within the alkaline Rainy Creek Complex are Na- and K-rich, exhibit a broad range in composition, and include the minerals richterite, tremolite, and winchite (Meeker et al. 2003). Those forms of fibrous amphiboles are referred to in this report as Libby-type amphiboles (LA).

Purpose and scope

In 2002, Libby was declared an U.S. Environmental Protection Agency (EPA) Superfund site. As part of the Superfund cleanup, soils contaminated with amphibole from Vermiculite Mountain are being removed within the town of Libby and surrounding areas. Unconsolidated sand that was believed to not have been contaminated by human releases from the mine or related activities was used as fill material to replace material removed during clean-up activities in the town of Libby. However, air sampling data collected by the EPA following clean-up suggest that the

Published online: 18 November 2010

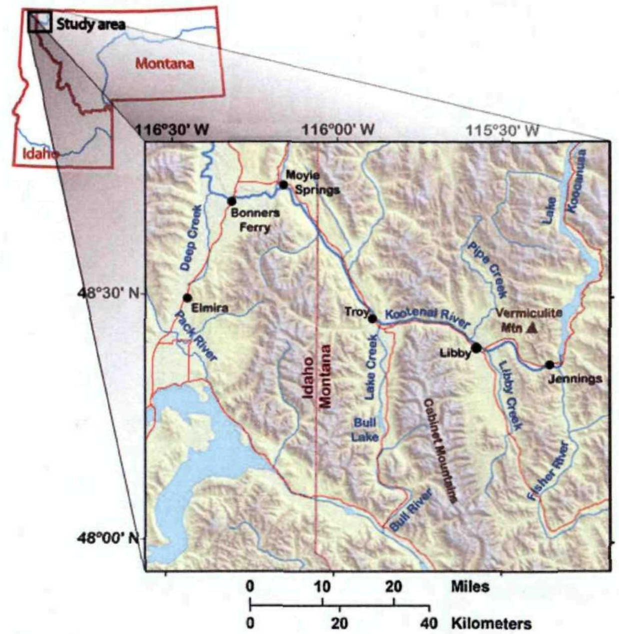

Fig. 1 Shaded relief index map showing major features and locations mentioned in study area

sand used for clean-up activities may contain LA fibers that were released into the air.

The question addressed here is whether some of the amphibole from Vermiculite Mountain was deposited in glaciofluvial sediments approximately 16,000 years before the present (ybp) rather than by human activity after vermiculite mining began. The EPA requested that the U.S. Geological Survey conduct a study to sample and analyze naturally occurring unconsolidated material (referred to as background soils) in the Libby area to determine the presence and distribution of the LA or other amphiboles similar to LA in composition. This study places constraints on the amount and location of possible naturally derived or "background" amphibole from Vermiculite Mountain in the Libby area.

The vast majority of unconsolidated material in the Libby area is the product of sediment mobilization and transport by Pleistocene glacial and glaciofluvial processes. Other geologic processes, including periglacial solifluction, mass wasting, and recent flooding mobilize and transport relatively small amounts of material from Vermiculite Mountain when compared to glacial scour and glaciofluvial transport. Therefore, this report describes only the glacial history of the Libby area, and considers the distribution of LA in the context of that history.

Study method

The glacial history portion of this paper is based on a landform and topographic analysis of the Libby area utilizing modern (1997) 1:24,000-scale topographic maps used in combination with data from the reports mentioned below, especially the report of Alden (1953). The glacial history of the area was reconstructed to: (1) help identify the source areas of LA found in the lake sediments (Adams et al. 2010), (2) to explain the occurrence of the LA, and (3) to help define the potential distribution of the LA.

The glacial geology of the Kootenai River valley surrounding Libby has been described in a very general manner by Smith (2006), and in more detail in Alden's classic reconnaissance study of the physiography and glacial geology of western Montana (Alden 1953), which includes maps of the physiography and glacial geology at a scale of 1:500,000. Alden (1953) also described the glacial geology of the region in Gibson (1948). Harrison and Cressman (1993) mapped the distribution of glacial deposits in northwest Montana at a scale of 1:125,000 as part of their study of the Libby Thrust Belt, but they did not discuss the glacial deposits in detail. Boettcher and Wilke (1978) mapped the lake-bottom deposits in the Libby area at a scale of 1:48,000 as part of a ground-water investigation. Two geologic maps in the Bonners Ferry, Idaho area provide insight to the history of Glacial Lake Kootenai: (1) a 1:24,000-scale map of the Elmira Quadrangle (Lewis et al. 2007), and (2) a 1:100,000-scale map of the Bonners Ferry quadrangle (Miller and Burmester 2003).

The Libby area is characterized by distinct mountain ranges and intervening valleys. The Kootenai River (spelled Kootenay for its Canadian portions) is the major stream traversing the Libby area (Fig. 1). It flows southward from Canada into the United States through Lake Koocanusa, northeast of Libby. Near Jennings, shortly after exiting Lake Koocanusa, the Kootenai River turns westward through Libby and Troy and northwestward to Bonners Ferry, Idaho. From there it flows northward back into Canada where it ultimately joins the Columbia River. Along the westward and northwestward stretch of the Kootenai River between Jennings and Bonners Ferry, tributaries located south of the river, including Fisher River, Libby Creek, Lake Creek, and Deep Creek, flow northward to join the Kootenai River.

During the Pleistocene, the northward paths of these rivers were blocked by ice as the glacier retreated. Water melting from glaciers, rainfall, or melting snow could not flow northward. Instead, the water ponded in the stream valleys in front of the retreating ice front, forming glacial lakes in the north-draining valleys. The water in the glacial lakes rose until it reached the lowest divide to an ice-free river, commonly at the southern end of each valley. Those divides, referred to in this report as glacial lake spillways, controlled the levels of the glacial lakes formed in the valleys in front of the ice.

All the figures in this report were prepared by the authors. The location of ice fronts were generated by the authors based primarily on geomorphology and constrained by highly generalized ice fronts from digital data in Ehlers and Gibbard (1996). The outlines of glacial lakes were generated from digital elevation data using a geographic information system. Lake-bottom deposits were digitized from Alden (1953) and from Boettcher and Wilke (1978). Glaciofluvial deposits were outlined on modern topographic maps by the authors, and confirmed by reference to Alden (1953) or Harrison and Cressman (1993). The authors correlated these deposits to specific glacial lake levels by comparing the altitudes of the deposits with the altitudes of the glacial lakes. Where necessary, corrections were made for post-glacial crustal rebound.

It should be noted that the altitudes described in this paper were derived from contour maps with 12.2 m (40 foot) contours. Therefore, the possible error in altitudes discussed in this report could approach 12.2 m. However, the difference in altitude between successive spillways is at least 30 m, which is well outside the error contained in the topographic maps.

Geology of the area

Metasedimentary rocks of the Mesoproterozoic Belt Supergroup underlie the area, although some Cretaceous and Tertiary intrusive rocks are also present (Harrison and Cressman 1993). The Rainy Creek igneous complex at Vermiculite Mountain, the source of the LA, is one such Cretaceous intrusion.

It should be noted that the LA-bearing rocks that comprise Vermiculite Mountain were emplaced as an alkaline, ultramafic intrusion, likely during the Early Cretaceous (Boettcher 1967). They were covered by rocks not known to contain LA. It is not known when the overlying rocks were stripped off, thus unroofing the LA-bearing deposit at Vermiculite Mountain. Presumably the overlying rocks were eroded away before or during one or more of the Pleistocene glaciations, thereby exposing the LA-bearing vermiculite deposit and other ultramafic rocks of the pluton.

Glacial history of the Libby area

It is well documented that the Cordilleran ice sheet originating in Canada advanced and retreated over western Montana at least three times during the Quaternary Period, although the ages of glacial episodes are poorly constrained (Locke and Smith 2004). Alden (1953) recognized these three glaciations in western Montana; from oldest to youngest they are the early pre-Wisconsin, Illinoian or Iowan, and Wisconsin. Richmond et al. (1965) correlate the early pre-Wisconsin with the pre-Bull Lake glaciation recognized elsewhere in the Rocky Mountains, the Illinoian or Iowan with the Bull Lake glaciation, and the Wisconsin with the Pinedale glaciation. This report focuses on the Pinedale, the most recent ice advance (ca. 25,000–16,000 ybp).

During the Pinedale, about 16,000 ybp, the Cordilleran ice sheet was at its maximum extent in the Libby, Montana, area (Fig. 2). The maximum thickness of the ice sheet at Jennings, near the confluence of the Fisher River with the Kootenai River, was about 1,220 m. The Kootenai River gorge between Jennings and Libby probably was occupied by ice. It is likely that the highest parts of the Cabinet Mountains southwest of Libby Valley were not overridden by the Cordilleran ice sheet, although numerous cirques in those mountains indicate the presence of valley glaciers that flowed into Libby valley. Ice probably covered all but the highest peaks on the ridges southeast of Libby that separate Libby valley from Fisher River valley (Alden 1948, 1953).

When the climate began to warm, gradual thinning of the ice at its distal end exposed the nearby mountain ridges near Libby and segregated the ice into individual valley lobes. Alden recognized three glacial lobes; from east to west—the East Kootenai Glacier, Troy Glacial lobe, and the Purcell Trench Glacier (Alden 1953). These correlate with the Thompson River lobe, Bull River lobe, and Lake Pend Oreille lobe, respectively, of Richmond et al. (1965).

The descriptive terminology of Alden (1953) relates better to the Libby area than does that of Richmond et al. (1965); therefore, this report adopts the terminology of

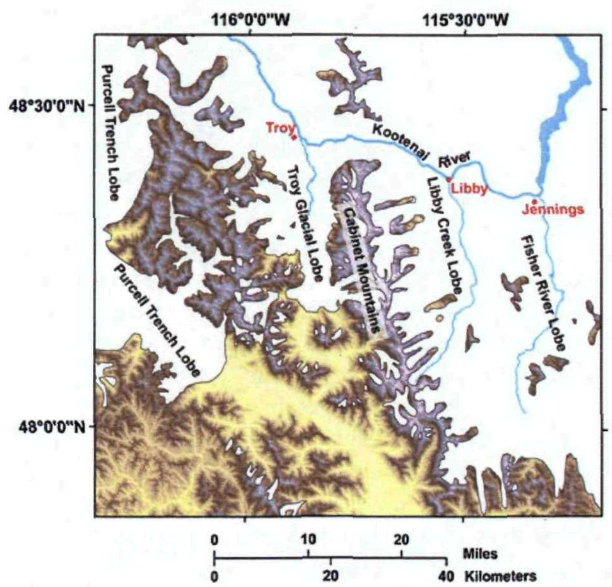

Fig. 2 Shaded relief map showing the maximum extent of the Fisher River Lobe, Libby Creek Lobe, Troy Glacier Lobe, and Purcell Trench Lobe of the Cordilleran Ice Sheet during the Pinedale glaciation in the Libby area

Alden (1953) with the following modifications: (1) The Purcell Trench Glacier is renamed the Purcell Trench Lobe, and (2) the East Kootenai Glacier is split into the Fisher River lobe in the Fisher River valley and the Libby Creek lobe in the Libby Creek valley (Fig. 2). The Libby Creek lobe, although not named by Richmond et al. (1965), was discussed in a cursory manor by Alden (1953).

The Fisher River, Libby Creek, Lake Creek, and Deep Creek are a series of north-flowing streams that empty into the Kootenai River (Fig. 1). As the northward-retreating ice lobes opened these valleys, ice-dammed lakes occupied the valleys. The opening of a spillway in one valley commonly initiated a series of cascading events that affected one or more of the other north-flowing drainages. As the shape of the ice front changed, the lowest outlet switched from one valley to another, resulting in a complicated, changing pattern of proglacial lakes. Initial ice retreat in each of the north-flowing valleys resulted in the formation of a high-level proglacial lake. Continued ice retreat or erosion of the controlling spillway led to the lowering of the lake. Eventually, the proglacial lakes within each valley opened into the Kootenai River valley, ultimately becoming an arm of the much larger Glacial Lake Kootenai.

Thompson Lakes Spillway

When the Cordilleran Ice Sheet first began to thin and the ice front began to retreat in the Libby area, the East Kootenai Glacier split into two lobes (Fig. 2); one extending up the Fisher River (the Fisher River lobe), and the other extending up Libby Creek (the Libby Creek lobe). At its maximum extent the Fisher River lobe extended southward past the Kootenai River valley and for 40 km up the valley of the Fisher River and its tributaries. A moraine near Thompson Lakes (Fig. 3) marks the southern limit of ice advance up the Fisher River valley (Alden 1953).

The Libby Creek lobe was one of the smaller lobes of Cordilleran ice (Alden 1953). Along the western flank of Libby Creek valley, local valley glaciers heading in the Cabinet Mountains extended eastward into Libby Creek valley and coalesced with the Libby lobe (Alden 1953). There is no well defined moraine to mark the maximum extent of ice up Libby Creek valley. However, till exposed in a road cut about 23 km south of Libby suggest that the ice extended at least that far. The till was clearly derived from rocks exposed to the north (Alden 1953). South of this till exposure, till deposits in Libby Creek valley were derived from local valley glaciers heading high in the Cabinet Mountains (Alden 1953). The till from the valley glaciers may overlie older till from the Libby lobe.

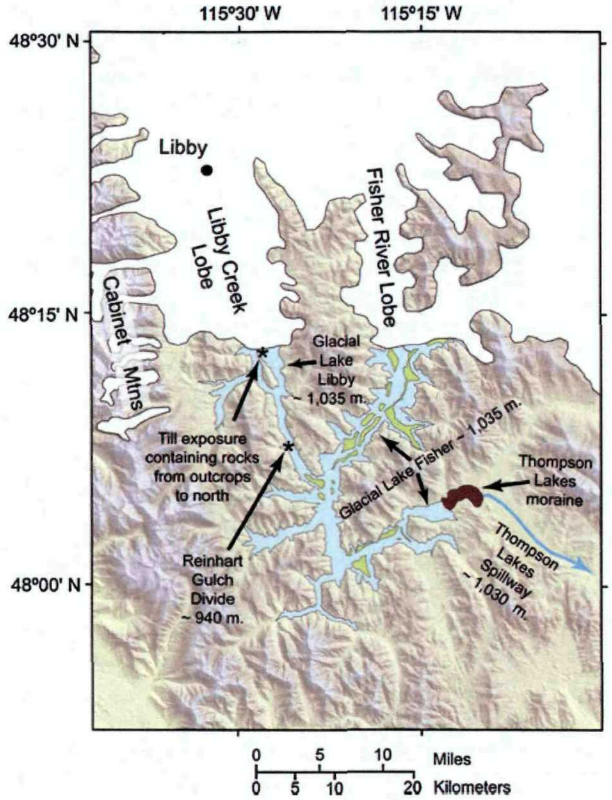

Fig. 3 Shaded relief map showing Cordilleran Ice Sheet (*white*), glacial lake-bottom deposits (*green*), glacial lakes (*blue*), Thompson Lakes moraine (*brown*), and Thompson Lakes Spillway (*blue arrow*)

As the ice sheet continued to shrink, proglacial lakes formed in front of the retreating ice lobes in the southern parts of the north-flowing Fisher River and Libby Creek valleys (Fig. 3). The water level of the lake in the Fisher River valley, herein referred to as Glacial Lake Fisher, was controlled by a spillway through the divide in the Thompson Lakes area that separates the Fisher River from the south-flowing Thompson River. The spillway is herein referred to as the Thompson Lakes Spillway. The altitude of the divide is about 1,030 m. Assuming there was about 5 m of water in the spillway, the surface of Glacial Lake Fisher would have stood at an altitude of about 1,035 m. The area inundated by Glacial Lake Fisher contains disconnected erosional remnants of lake-bottom deposits, some of which have upper surfaces at altitudes at or just below the hypothesized level of the lake.

The lake in Libby Creek valley, herein referred to as Glacial Lake Libby, expanded southeastward across a low divide near Reinhart Gulch standing at about 940 m altitude between the Libby Creek and Fisher Creek drainages. Glacial Lake Libby coalesced with Glacial Lake Fisher, and both lakes drained southward through the Thompson Lakes Spillway (Fig. 3).

Ross Creek Spillway

The Troy Glacial lobe (Figs. 2, 4), located in the first major valley west of Libby, advanced about 24 km southward past Troy, and up Lake Creek valley to a point just south of the divide between Lake Creek and the Bull River (Fig. 1). The termination is marked by a moraine that extends eastward across the Lake Creek valley (Alden 1953), herein referred to as the Ross Creek moraine (Figs. 4, 5). Remnants of the moraine stand at an altitude of about 825 m. The Troy ice lobe was restricted to Lake Creek valley and did not cover the ridges on either side of the valley (Fig. 2). Mountain glaciers on either side of Lake Creek flowed into the valley, coalescing with the ice lobe in the valley (Alden 1953).

Water ponded between the retreating ice front and the Ross Creek moraine forming a proglacial lake herein referred to as High-level Glacial Lake Troy (Fig. 4). The outflow from the lake was through the bedrock-floored draw (altitude about 810 m) on the western side of the Ross Creek moraine. What remained was a situation analogous to a modern earthen dam with a concrete spillway; the dam impounds the water and the concrete spillway provides a stable, resistant outlet for the lake behind the dam. The spillway is herein referred to as the Ross Creek Spillway.

High-level Bull Lake Spillway

Eventually, water leaking through the earthen dam formed by the Ross Creek moraine caused the dam to fail. Glacial Lake Troy drained to a new, lower level (755 m) contained by an extensive valley-train deposit (Fig. 5) in the Bull River valley from its divide with Lake Creek, approximately 0.8 km south of Bull Lake, to a moraine 14 km down the Bull River. The 750-m spillway (plus about 5 m of water in the spillway), herein referred to as the High-level Bull Lake Spillway, controlled the water level of Glacial Lake Troy (about 755 m).

Continued thinning of the Troy Glacial lobe, in combination with the steep topography north of Troy, caused the southern portion of Troy Glacial lobe to detach from the Cordilleran ice sheet, leaving stagnant ice in Lake Creek valley (Fig. 5). Stagnant ice near the confluence of Lake Creek with the Kootenai River is indicated by collapsed ice contact deposits southeast of Troy. These ice contact deposits probably had the active ice lobe in the Kootenai River to the northwest as their source (Alden 1953).

Similarly, thinning ice and steep topography caused the Libby Creek lobe to detach from the Cordilleran ice sheet, leaving stagnant ice in Libby Creek valley (Fig. 5). When the Lake Creek valley south of Troy and the Kootenai

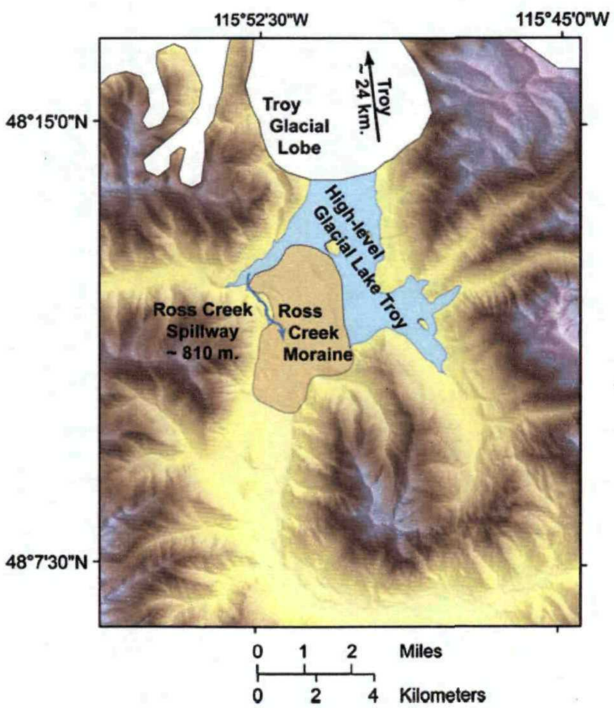

Fig. 4 Shaded relief map showing High-level Glacial Lake Troy formed in Lake Creek valley between Ross Creek Moraine and the Troy Lobe. The lake level was controlled by the Ross Creek Spillway

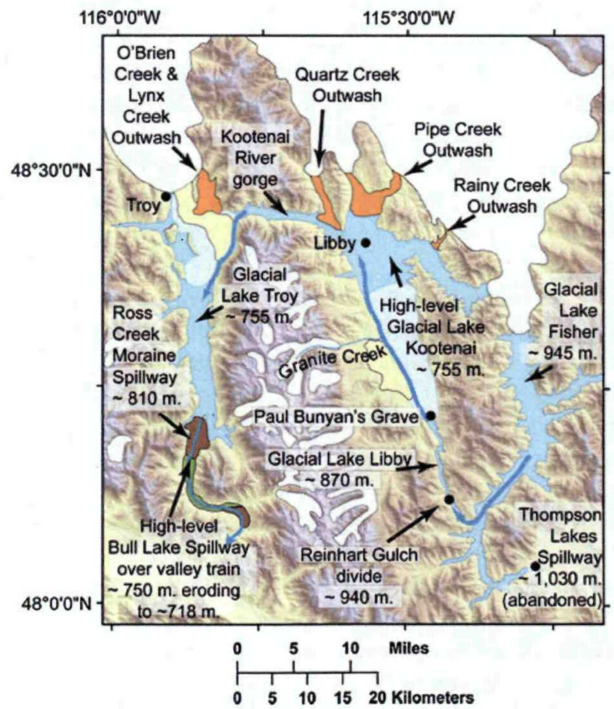

Fig. 5 Shaded relief map showing glacial lakes (*blue*) controlled by High-level Bull Lake Spillway, direction of water flow in lakes (*blue arrows*), Cordilleran Ice Sheet (*white*), stagnant ice (*white with blue stipples*), moraines (*brown*), outwash (*orange*), valley-train (*green*), and collapsed ice contact deposits (*tan*)

River gorge west of Libby both became free of active ice, Glacial Lake Libby drained around or over the stagnant remnant of the Libby lobe, westward through Kootenai gorge, into Glacial Lake Troy, discharging through the Ross Creek Spillway, and subsequently through the High-level Bull Lake Spillway (Figs. 4, 5). When this happened, Glacial Lake Fisher abandoned its drainage through the Thompson Lakes Spillway (1,030 m), and drained over the Reinhart Gulch divide (940 m) into Glacial Lake Libby. When the active ice lobes retreated from the Fisher River Valley, Libby Creek Valley, and from the Kootenai River gorges east and west of Libby, the glacial lakes in those areas coalesced to form one large lake, herein referred to as High-level Glacial Lake Kootenai.

Sediment carried by water flowing from valley glaciers to the west was deposited on top of the stagnant ice in Libby Creek valley and between the stagnant ice and the western valley side. When the stagnant ice melted, the sediment collapsed, resulting in the hummocky topography such as that south of Granite Creek (Fig. 5). The uncollapsed tops of the deposit are at about 870 m.

About 19 km south from Libby, fine-grained lake-bottom sediments in Libby Creek valley underlie a landform locally referred to as Paul Bunyan's Grave (Fig. 5). The lake-bottom sediments are about 15 m thick, overlie till, and are capped with gravel that is approximately on grade with the previously described ice contact deposits near Granite Creek (870 m). The gravel cap on Paul Bunyan's Grave, and the ice contact deposits near Granite Creek, probably were deposited while Glacial Lake Fisher drained northward through the Reinhart Gulch spillway over or along side of the stagnant lobe of ice in Libby Valley towards Troy. The source of sediment was probably outwash from mountain glaciers in the Cabinet Mountains to the west.

The Libby region probably experienced post-glacial rebound following deglaciation. Correlating the altitudes of deposits in various glacial lakes with the surface levels of those glacial lakes requires an understanding of the crustal rebound. The area to the north (i.e., at the latitude of Libby and Troy) rebounded greater than the area to the south (i.e., the Bull Lake Spillway area) because the ice around Libby and Troy was thicker and compression was greater than at the Bull Lake Spillway. The authors were not able to locate any published figures on the amount of glacial rebound in the area; however, uplift in the area was calculated to be about 0.9 m/km (discussed later in this report).

Pipe Creek, Quartz Creek, and Rainy Creek near Libby, and the O'Brien/Lynx Creek drainages near Troy, all deposited sediment into Glacial Lake Kootenai when it was controlled by the High-level Bull Lake Spillway (Fig. 5). The surfaces on the glacial outwash deposits in the valleys of Quartz Creek, Rainy Creek, and the O'Brien/Lynx Creeks, all are approximately 762 m, or 738 m adjusted for rebound. Outwash from those drainages was deposited into Glacial Lake Kootenai while the High-level Bull Lake Spillway (755 m or 760 m when including 5 m of water in the spillway) was being eroded to the lower Bull Lake Spillway (718 m or 723 m when including 5 m of water in the spillway) level (discussed below). High-level Lake Kootenai was relatively short-lived, probably because the valley-train deposits controlling its base level were easily erodible. Eventually, the spillway eroded through the sediments to bedrock and stabilized at an altitude of about 718 m.

Bull Lake Spillway

By the time the High-level Bull Lake Spillway eroded to an altitude of 718 m, the Cordilleran ice sheet had retreated northward to where the melting ice front no longer contributed meltwater to Quartz Creek or Rainy Creek, near Libby (Fig. 6). Stagnant remnants of the ice lobes had melted from the valleys. Rainy Creek was abandoned as a meltwater conduit when the ice front retreated north of Blue Mountain, which is located 6 km northwest of Vermiculite Mountain.

Pipe Creek, near Libby, and Lynx Creek, north of Troy, continued to transport meltwater from the ice front to Glacial Lake Kootenai. Pipe Creek deposited large

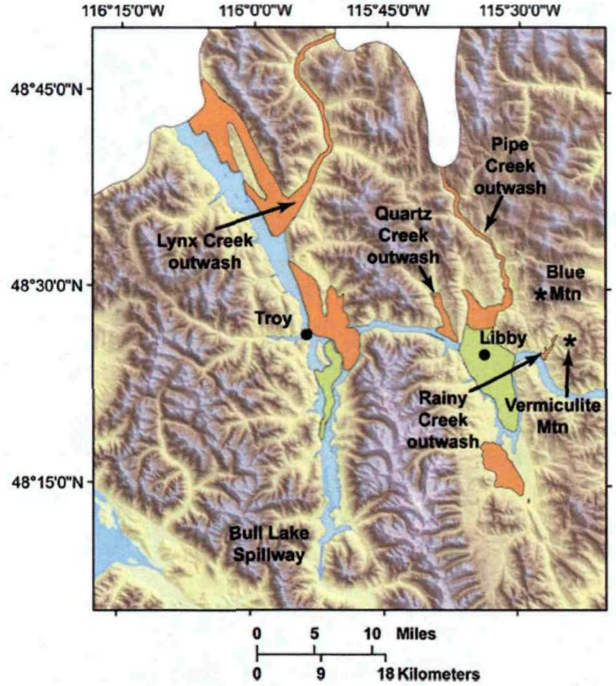

Fig. 6 Shaded relief map showing Glacial Lake Kootenai (*blue*) when controlled by the Bull Lake Spillway, Cordilleran ice sheet (*white*), outwash deposits (*orange*), and lake-bottom deposits (*green*)

amounts of lake-bottom sediments into the lake (Fig. 6). Lake-bottom sediments once extended from Pipe Creek to 13 km southward up the Libby Creek valley. Lake-bottom sediments in a bluff east of Libby are 90 m thick, almost massive, without distinct laminae, and they contain no pebbles, boulders, or fossils (Alden 1953). The sediments underlying Libby Valley are about 30 m thick, as estimated from Boettcher and Wilke (1978). These combined observations suggest about 120 m total thickness of lake-bottom sediments in the Libby area.

Where Pipe Creek discharged its sediment into Glacial Lake Kootenai, it built a large delta, herein referred to as the Pipe Creek delta (Fig. 7). The morphology and sedimentary structure of Pipe Creek delta were used to estimate the altitude of Glacial Lake Kootenai at Pipe Creek. Alden (1953) described an exposure of the Pipe Creek delta where 15 m of stratified, sandy silt overlies till, which is overlain by about 6 m of coarse cobble-gravel (Fig. 7). The base of these gravels mark the contact between subaerial (coarse) gravels and lake-bottom (sandy silt) sediments. The contact between the coarse gravel and sandy silt, as estimated from a modern topographic map, is about 747 m, providing one estimate of the level of Glacial Lake Kootenai at the latitude of the Pipe Creek delta.

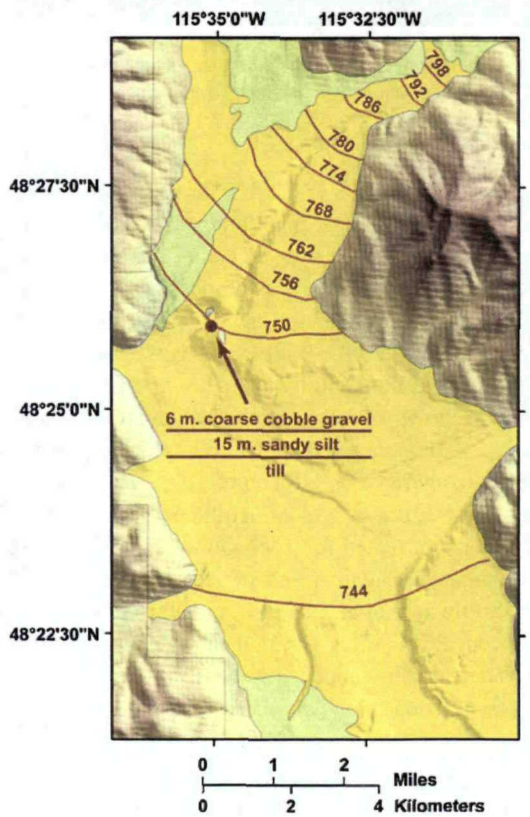

Fig. 7 Contours (in meters) showing reconstructed surface on Pipe Creek delta. Pipe Creek location is shown on Fig. 6 (contours originally plotted in 20-foot intervals)

Through a landform reconstruction process it was possible to provide a second estimate of the lake level at Pipe Creek. The original shape of the Pipe Creek delta was reconstructed by drawing contours connecting the highest points on the non-eroded surface of the landform as shown on modern topographic maps (Fig. 7). A distinct change in gradient occurs on the surface of the delta between the 750 m (2,460 foot) and 744 (2,440 foot) contours. The change in gradient is presumed to separate the part of the delta that was deposited subaerially (the steeper gradient on the surface of sediments) from that deposited subaqueously (the flatter gradient on the sediments).

These two measurements tentatively establish a lake level of Glacial Lake Kootenai at the latitude of Pipe Creek of about 747 m. The lake level, as defined by the altitude of the Bull Lake Spillway (718 m), and allowing about 5 m of water in the spillway, was calculated to be about 723 m, which results in a difference of about 24 m. The Pipe Creek delta is about 27 km up-ice from the Bull Lake Spillway, resulting in a calculated post-glacial uplift rebound of about 0.9 m/km.

The maximum ice thickness and underlying bedrock in southern New England is similar to that in the Libby area. Post-glacial rebound in southern New England was calculated to be about 0.8 m/km (Jahns and Willard 1942), which is similar to that calculated for the Libby area.

Elmira Spillway

When the Purcell Trench lobe retreated northward of the Kootenai River valley near Moyie Springs, Idaho, discharge from Glacial Lake Kootenai abandoned the Bull Lake Spillway (718 m) and changed course through Bonners Ferry, southward over a divide near Elmira, Idaho (Fig. 8). Glacial lake-bottom sediments occur in Paradise Valley to an altitude of about 700 m, documenting the existence of a lake at that level. Ultimately, discharge from Glacial Lake Kootenai eroded down to bedrock at the divide at about 655 m that separates the north-flowing Deep Creek from the south-flowing Pack River (Fig. 1) near Elmira, Idaho, herein referred to as the Elmira Spillway.

With the lowering of Glacial Lake Kootenai, the lake-bottom deposits in the Libby area that were once under water were left high and dry. While Glacial Lake Kootenai was draining, the lake took the form of a braided river system that meandered across the lake-bottom deposits in Libby valley and elsewhere, cutting downward, laterally, and headward through the lake-bottom deposits. Multiple gravel-capped terraces were cut into the Pipe Creek delta between 730 m and the Kootenai River (Alden 1953). This includes a prominent terrace and large sand bar in the Pipe Creek delta, a terrace at an altitude of about 700 m, and the bar deposit at about 715 m (Fig. 9). Eventually headward

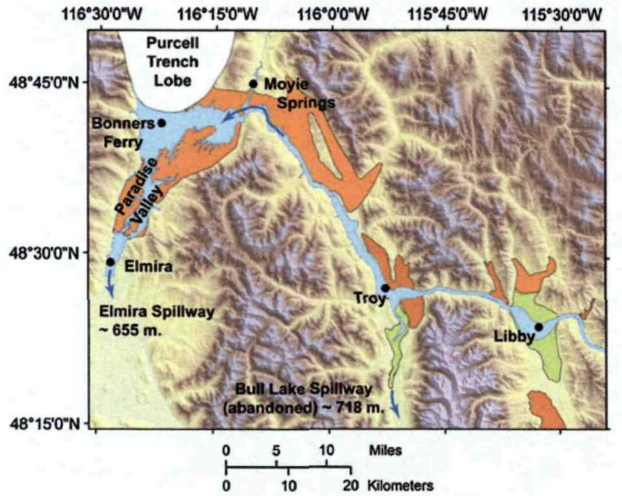

Fig. 8 Shaded relief map showing Glacial Lake Kootenai (*blue*) when controlled by Elmira Spillway, major outwash deposits (*orange*), and lake-bottom deposits (*green*)

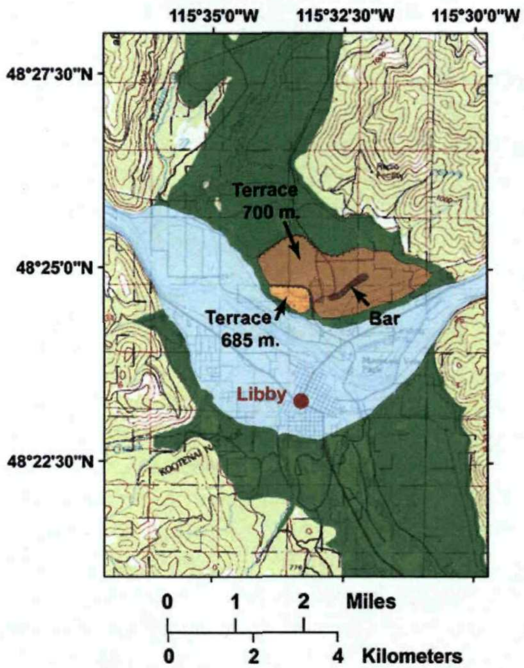

Fig. 9 Map showing Glacial Lake Kootenai (*blue*) as controlled by the Elmira Spillway, terraces deposited on eroded surfaces on glacial lake-bottom deposits, and bar built on 700-m terrace

erosion resulted in the creation of a much narrower, lower level Glacial Lake Kootenai.

Glacial re-advance

As the Elmira Spillway was being eroded to its lower (655 m) level, the Purcell Trench lobe readvanced at least once, damming the Kootenai River valley at Moyie Springs. This resulted in the partial refilling of Glacial Lake Kootenai. Figure 10 shows an exposure in Glacial Lake Kootenai sediments that demonstrate the re-advance. The gravel/sand layer is at an altitude of about 665 m. The imbrication and clast-on-clast support of the gravel/sand layer indicates that channel gravels deposited as the water eroding through the lake-bottom deposits was adjusting to the lowering Elmira Spillway. The fine-grained, thinly laminated sediments overlying the gravel are interpreted as lacustrine sediments deposited into a glacial lake created by the readvancing Purcell Trench lobe. The lake-bottom sediments accumulated to an altitude of at least 685 m before the ice retreated for a second time. When the Moyie Springs area was again freed of ice, reoccupation of the Elmira Spillway and an increase in water velocity resulted in renewed downcutting through the deposits and the formation of a gravel-capped terrace at an altitude of about 685 m (Fig. 9) on the newly formed lake-bottom deposits.

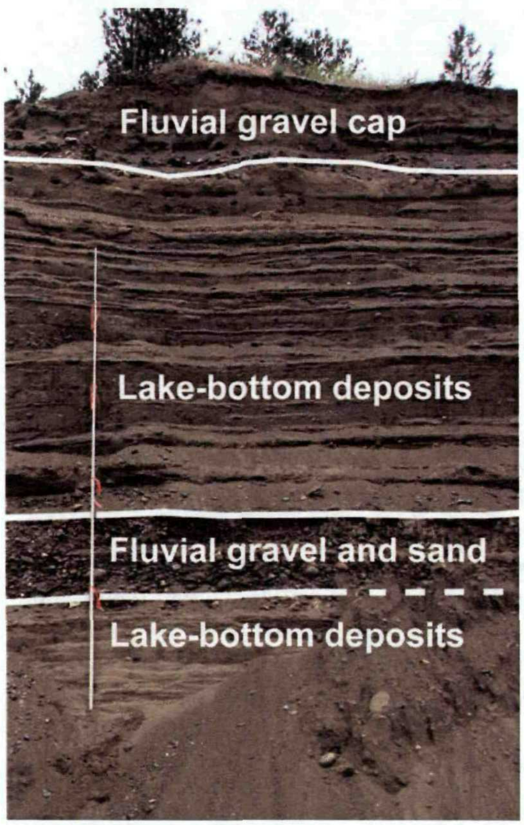

Fig. 10 Exposure in Glacial Lake Kootenai sediments demonstrating glacial re-advance near Moyie Springs. *Orange* flagging on stadia rod at 1.52-m intervals. The gravel and sand layer is at an altitude of about 665 m

Final draining of Glacial Lake Kootenai

Around 11,000 years ago (Ehlers and Gibbard 1996), the northernmost route of the Kootenai River was freed of ice, and the river occupied its present-day course to the

Columbia River. A number of lower terraces were cut into the lakebed deposits, including the gravel-armored terrace at about 630 m on which the town of Libby is located.

Distribution of LA in Glacial Lake Kootenai sediments

Adams et al. (2010) describe analytical results from sediment samples collected from three localities near Libby, Montana (Fig. 11), for the purpose of determining the local background levels of LA that could potentially be derived from the nearby Rainy Creek Complex mined at Vermiculite Mountain.

Non-fibrous tremolite is a common rock-forming mineral in many igneous and metamorphic rocks and is likely present in many of the rock units surrounding Libby valley. Small quantities of non-fibrous tremolite derived from sources other than the Rainy Creek Complex would, therefore, not be unusual in soils and sediments sampled in and around Libby. Tremolite from other sources, however, would not be expected to contain appreciable amounts of Na and K, as does the tremolite from Vermiculite Mountain. Thus, it is likely that any fibrous Na- and K-rich tremolite, along with richterite and winchite, found in soils and sediments of the Libby Valley are derived from the Rainy Creek Complex at Vermiculite Mountain.

The lake-bottom deposits in the Libby area are about 120 m thick. It was not practical or necessary to sample the total thickness because most of the sediments are deeply buried and are not near the accessible environment. The consolidated sediment samples were collected from discrete layers of lake sediment deposited in Glacial Lake Kootenai and from Pleistocene terrace alluvium based in part on their environment of deposition: (1) a locality termed the "sand pit", containing primarily sand-sized particles, representing a shallow lacustrine or fluvial environment; (2) a locality termed the "clay pit", containing primarily clay-sized and silt-sized particles, representing a deep lacustrine environment; and (3) an undisturbed field containing primarily cobble-gravel and sand-sized particles representing a modern surface developed on Pleistocene alluvium. The sand pit site was also selected because fill had been obtained from that site for use in EPA clean-up activities.

Seventy samples were collected and examined using a scanning electron microscope equipped with an energy dispersive X-ray spectrometer. All samples contained varying amounts of feldspars, ilmenite, magnetite, quartz, clay minerals, pyroxene minerals, and non-fibrous amphiboles such as tremolite, actinolite, and magnesiohornblende. Of the 70 samples collected and analyzed, only four samples contained LA, which in all cases was less than 0.1% by weight.

LA-bearing lake-bottom sediments associated with the Rainy Creek delta

Two samples containing LA came from layers of very fine-grained sediment at the base of the exposed cliff face in the clay pit (Fig. 12). LA concentrations range from approximately 0.02 to 0.05% in Layer 1; and from non-detect to 0.04% in Layer 2 (Adams et al. 2010).

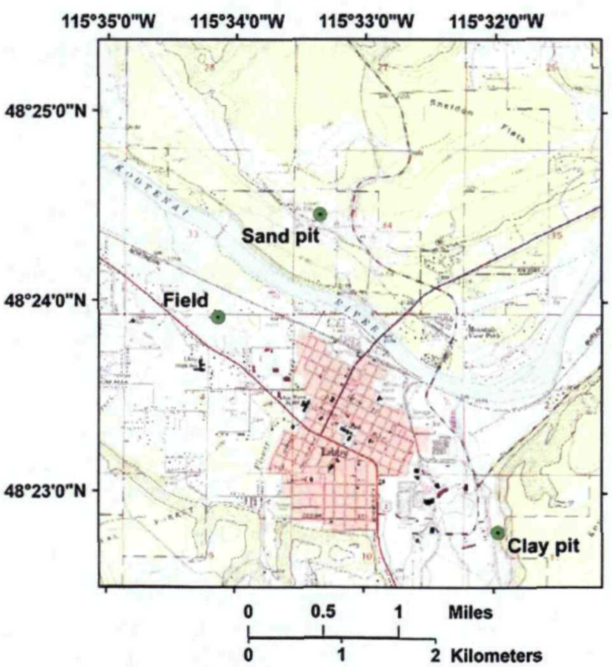

Fig. 11 Map showing location of sample sites for background levels of LA

Fig. 12 Sample sites from clay pit (*white boxes*), and two sample localities containing LA (*labeled*). More detail is shown on the *inset photos*

The LA in these sediments probably originated at Vermiculite Mountain and were deposited into Glacial Lake Kootenai during the High-level Bull Lake stage (755 m), concurrent with the deposition of other sediments into Glacial Lake Kootenai from Pipe Creek, Quartz Creek, and the Kootenai River. As the active ice front retreated up Rainy Creek valley, but still covered Vermiculite Mountain, glaciofluvial sediments were transported down Rainy Creek (Fig. 5). The coarse sediments were deposited as a delta into Glacial Lake Kootenai, which is preserved today as a high terrace near the present-day confluence of Rainy Creek and the Kootenai River. The fine-grained sediments sampled were carried into Glacial Lake Kootenai and deposited with sediments from other sources in two thin, discrete, closely spaced layers of lake-bottom deposits. Most places where these layers occur are covered with over 30 m of other fine-grained sediments not containing amphiboles from Vermiculite Mountain. If the LA-bearing layers are pervasive, they would only be exposed in the faces of bluffs (Fig. 13).

LA-bearing lake-bottom sediments associated with the Purcell Trench lobe re-advance

One sample containing LA came from the sand pit (Fig. 11). The LA was in a clayey silt layer (altitude 655 m) underlain by 1.4 m of cobble pebble gravel with coarse sand (Fig. 14). The LA concentrations range from approximately 0.059 to 0.082%. The LA-bearing fine-grained deposit overlying the gravel is interpreted as lake-bottom sediments deposited into a glacial lake formed behind the readvancing Purcell Trench lobe near Moyie Springs. The LA occurring in the layer most likely was eroded from the delta deposit at the confluence of Rainy Creek and the Kootenai River while Glacial Lake Kootenai was adjusting to its new base level. If the LA-bearing layer is pervasive, it is limited to the deposits underlying the 685-m terrace (Figs. 9, 15) and would be exposed only in the faces of bluffs.

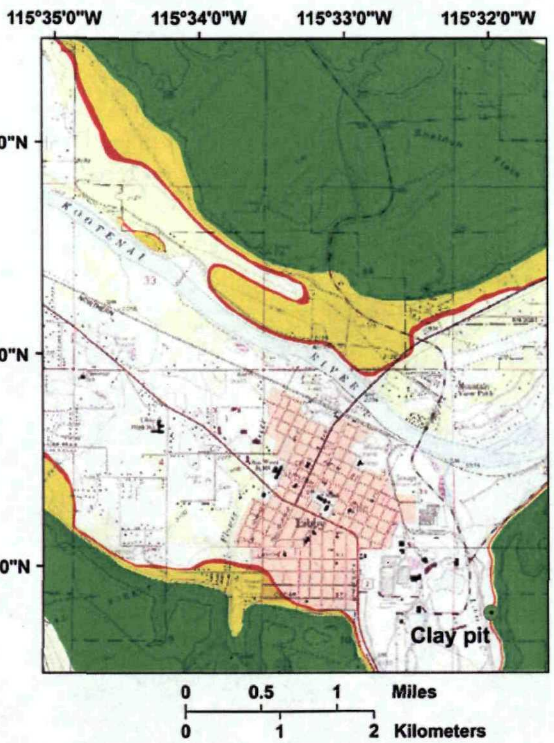

Fig. 13 Thickness of material overlying LA-bearing layer in lake-bottom sediments, if they are pervasive: *red* 0–6 m, *yellow* 6–15 m, *green* >16 m. Possible exposures of LA-bearing layers occur only as thin layers in *red areas*

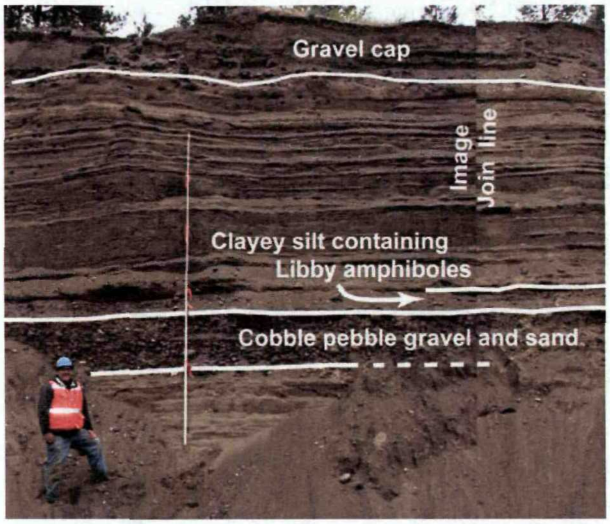

Fig. 14 Photograph of sand pit showing fluvial cobble-gravel layer overlain with lake-bottom deposits, capped with fluvial terrace gravel

LA-bearing fluvial gravel

The final sample containing LA is from an undisturbed (i.e., unexcavated) field near a location where fill soil had been previously excavated for use in clean-up activities (Fig. 11). Samples were taken from three shovel holes made in the field. The sample containing LA from this locality was from a zone 51–56 cm below the surface. The sediment was alluvial cobble pebble gravel with silty sand in the interstices. LA occurred at a concentration ranging from approximately <0.01% to approximately 0.05% by weight of the fine-grained portion of the sample.

LA was only detected in one sample horizon from one hole; other samples taken from two nearby holes contained no detectable LA. The origin of the LA in this sampled deposit is uncertain. The LA could be of fluvial origin deposited with the alluvial gravels, or could be mined material transported to the sampled horizon by water

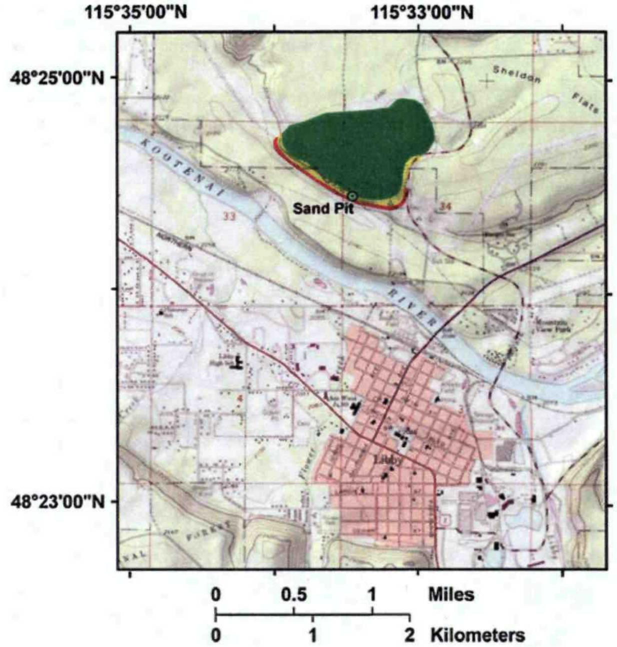

Fig. 15 Thickness of material overlying LA in 658-m terrace: *red* 0–6 m, *yellow* 6–30 m, *green* >30 m. Possible exposures of LA-bearing layers occur only as a thin layer in *red areas*

percolating through the vadose zone. No prediction of the distribution of LA at this location was made because of insufficiency of data.

Summary

The town of Libby is underlain with glacio-lacustrine and glacio-fluvial sediments deposited into Glacial Lake Kootenai. The lake was controlled by multiple spillways, resulting in multiple lake levels. From our reconstruction of the history of Glacial Lake Kootenai, we conclude that most of the sediment in the lake near Libby came from sources other than Vermiculite Mountain. There were two situations where sediments derived from Vermiculite Mountain were deposited into Glacial Lake Kootenai: (1) as lake-bottom sediments associated with the Rainy Creek delta, deposited when Rainy Creek valley south of Vermiculite Mountain was free of ice but the ice sheet covered Vermiculite Mountain; and (2) as lake-bottom sediments eroded from the Rainy Creek delta and re-deposited during a re-advance of the Purcell Trench Glacier lobe. The layers of sediment containing LA are a few centimeters thick and are covered by at least 15 m of material. If pervasive, they would only be exposed at the land surface in the faces of bluffs. A sample of Pleistocene alluvial gravel underlying a field near Libby contained LA. It is uncertain whether the LA was of natural origin or was a product of mining.

References

Adams DT, Langer WH, Hoefen TM, Van Gosen BF, Meeker GP (2010) Examination of Libby, Montana, fill material for background levels of amphibole from the Rainy Creek complex using scanning electron microscopy and X-ray microanalysis. U.S. Geological Survey Open-File Report 2010-1056, 10 pp

Alden WC (1948) Pleistocene glaciation. In: Gibson R (ed) Geology and ore deposits of the Libby quadrangle, Montana—with sections on glaciation by W. C. Alden and physiography by J. T. Pardee. U.S. Geological Survey Bulletin 956, pp 49–61

Alden WC (1953) Physiography and glacial geology of western Montana and adjacent areas. U.S. Geological Survey Professional Paper 231, 200 pp, 4 plates

Boettcher AL (1967) The Rainy Creek alkaline-ultramafic igneous complex near Libby, Montana—I: ultramafic rocks and fenite. J Geol 75(5):526–553

Boettcher AJ, Wilke KR (1978) Ground-water resources in the Libby area, northwestern Montana. Montana Bureau of Mines and Geology Bulletin 106, 36 pp

Ehlers J, Gibbard PL (eds) (1996) Disc 1, Quaternary glaciations—extent and chronology, part II—North America: developments in Quaternary science 2. Elsevier, Amsterdam

Gibson R (1948) Geology and ore deposits of the Libby quadrangle, Montana—with sections on glaciation by W. C. Alden and physiography by J. T. Pardee. U.S. Geological Survey Bulletin 956, 131 pp

Harrison JE, Cressman ER (1993) Geology of the Libby Thrust Belt of Northwestern Montana and its implications to regional tectonics. U.S. Geological Survey Professional Paper 1524, 42 pp, 2 plates, 1:125,000 scale

Horton DK, Bove F, Kapil V (2008) Select mortality and cancer incidence among residents in various U.S. communities that received asbestos-contaminated vermiculite ore from Libby, Montana. Inhal Toxicol 20(8):767–775

Jahns RH, Willard ME (1942) Late Pleistocene and recent deposits in the Connecticut Valley, Massachusetts. Am J Sci 240(3): 161–191; 240(4):265–287

Lewis RS, Burmester RF, Breckenridge RM (2007) Geologic map of the Elmira quadrangle, Bonner County, Idaho. Idaho Geological Survey Digital Web Map 90, 1:24,000 scale

Locke W, Smith LN (2004) Pleistocene mountain glaciation in Montana, USA. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations—extent and chronology, part II—North America: developments in Quaternary science 2. Elsevier, Amsterdam, pp 125–129

Meeker GP, Bern AM, Brownfield IK, Lowers HA, Sutley SJ, Hoefen TM, Vance JS (2003) The composition and morphology of amphiboles from the Rainy Creek complex, near Libby, Montana. Am Mineral 88(11–12):1955–1969 (Part 2)

Miller FK, Burmester RF (2003) Geologic map of the Bonners Ferry 30′ × 60′ quadrangle, Idaho and Montana. U.S. Geological Survey Miscellaneous Field Studies Map MF-2426, 1:100,000 scale

Peipins LA, Lewin M, Campolucci S, Lybarger JA, Miller A, Middleton D, Weis C, Spence M, Black B, Kapil V (2003) Radiographic abnormalities and exposure to asbestos-contaminated vermiculite in the community of Libby, Montana, U.S.A. Environ Health Perspect 111(14):1753–1759

Richmond GM, Fryxell R, Neff GE, Weis PL (1965) The Cordilleran Ice Sheet of the northern Rocky Mountains, and related quaternary history of the Columbia Plateau. In: Wright HE Jr, Frey DG (eds) The Quaternary of the United States. Princeton University Press, Princeton, NJ, pp 231–242

Smith LN (2006) Pleistocene glacial deposits in the Libby and Lake River valley areas, Lincoln County, Montana. Northwest Geol 35:87–90

Sullivan PA (2007) Vermiculite, respiratory disease, and asbestos exposure in Libby, Montana—update of a cohort mortality study. Environ Health Perspect 115(4):579–585